TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE AERODYNAMIC CHARACTERISTICS OF AIRFOILS AS AFFECTED BY SURFACE ROUGHNESS

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Washington
April, 1933

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SUMMARY

The effect on airfoil characteristics of surface roughness of varying degrees and types at different locations on an airfoil was investigated at high values of the Reynolds Number in the N.A.C.A. variable-density wind tunnel.

Tests were made of a number of N.A.C.A. 0012 airfoil models on which the nature of the surface was varied from a rough to a very smooth finish. The effect on the airfoil characteristics of varying the location of a rough area in the region of the leading edge was also investigated. Airfoils with surfaces simulating lap joints were also tested.

Measurable adverse effects were found to be caused by small irregularities in airfoil surfaces which might ordinarily be overlooked. The flow is sensitive to small irregularities of approximately 0.0002c in depth near the leading edge. The tests made on the surfaces simulating lap joints indicate that such surfaces cause small adverse effects.

Additional data from earlier tests of another symmetrical airfoil are also included to indicate the variation of the maximum lift coefficient with the Reynolds Number for an airfoil with a polished surface and with a very rough one.

INTRODUCTION

For some time it has been generally recognized that discrepancies in the results of tests of geometrically similar airfoils tested in different wind tunnels can be attributed in part to scale and turbulence effects. Surface roughness, although generally conceded to have some effect on the aerodynamic characteristics of an airfoil, has not been given much consideration in the past.

Prediction of the effect of surface roughness at high values of the Reynolds Number from available low-scale data is practically impossible. Warner (reference 1) discusses early low-scale tests made on roughened surfaces, none of which caused much effect on the value of the maximum lift coefficient. Mention is also made of attempts to augment the lift of an airfoil by roughening the lower surface and by the use of grooves. Warner concludes that extreme roughness on the surface of an airfoil is probably injurious to the performance and that tests at higher values of the Reynolds Number are needed.

The fact that very small variations in surface conditions must be taken into account in airfoil testing at large values of the Reynolds Number has been known at this laboratory for some time. Foreign matter in the air stream of the variable-density wind tunnel was found to produce sufficient pitting and roughening of the airfoil surface to cause measurable adverse effects on the characteristics of an airfoil. The removal of the foreign matter and the repolishing of the surface always resulted in the disappearance of the adverse effects. Insufficient polishing of airfoil models was also found to have essentially the same effect as that caused by pitting on the surface.

Thus it became evident that an investigation which would establish the necessary degree of polish of the airfoil surface to eliminate the surface-condition variable would be very useful. Tests from wind tunnels where the surface condition of the airfoil models is known could then be more accurately interpreted and the effects of certain types of surface roughness found on airplanes now in service could be more accurately estimated. Tests were therefore made in the variable-density tunnel to investigate the effect of surface roughness on airfoil characteristics. In these tests the amount, position, and nature of the roughness were varied.

TESTS AND MODELS

The tests were conducted in the variable-density wind tunnel described in reference 2 and the method of testing was essentially the same as that described therein. The Reynolds Number was approximately 3,100,000. The majority of the tests were made with the N.A.C.A. 0012 symmetrical section, four individual airfoils of this section being used in the tests. One cambered section of medium thickness, N.A.C.A. 4412, was also included. The profiles of both airfoil sections are shown in their respective plots. All the airfoils used were 5 inches by 30 inches and were constructed of metal with the exception of one N.A.C.A. 0012 model which was constructed of laminated boxwood.

Surfaces

At different steps in the production of a standard metal airfoil for tests in the variable-density wind tunnel, variations in the surface condition of the model are obtained ranging from a rough to a very smooth finish.

The first surface tested was that of the airfoil as it comes from the generating machine; it will be referred to as "machine-cut" finish. This surface has an irregular wavy appearance caused by the chatter marks left by the cutting tool. Measurement of the surface disclosed that none of the irregularities or chatter marks on the surface were more than 0.0005 inch in depth. These irregularities were smoothly faired with no sharp breaks presented to the air stream. However, as can be seen from the photomicrograph in Figure 1, there was a sort of corner formed between successive cuts which is parallel to the chord of the airfoil.

Photomicrographs were taken of each surface, but as variations in the method of illuminating the surface produced greater changes in the photographic impression than did actual physical changes in the surface, they do not convey a true impression of the actual roughness. As the photographic impressions of the surfaces with abrupt breaks or wavy surfaces were the ones most nearly resembling the actual surface, only photomicrographs of two of these surfaces are shown.

The second surface was produced by rubbing with No.150

Alumnox cloth parallel to the span; it will be referred to as "rough-emery" finish. A variation of this rough-emery-finished surface was also tested in which the leading edge was polished for a distance of approximately 3 or 4 per cent of the chord.

The third surface was obtained by the use of finer grades of Alumnox cloth, finally finishing with the No. 180 grade cloth in a direction parallel to the chord of the airfoil. The model was then polished with rouge on a buffing wheel in alternate directions, the final polishing being parallel to the chord of the airfoil. This is the highly polished, or standard, surface and is perfectly smooth to the touch and presents to the eye a mirror-like surface, broken only by a few visible scratches. The depth of the scratches was ascertained by careful measuring to be in the order of 0.0005 inch, which in terms of the chord is 0.0001c.

Two different finishes were applied to the boxwood airfoil. The first was produced by applying two coats of varnish to the airfoil. This surface, although finished with fine sandpaper, had irregularities that could be detected by touch. The second surface was highly polished and was obtained by using several coats of varnish and polishing after each application until a finish was obtained comparable to that found on high-grade furniture.

A limited area on the surface of one of the N.A.C.A. 0012 airfoils was roughened at various positions near the leading edge for the investigation of roughness position. A striated area was produced by scribing grooves approximately 0.001 inch deep and 0.001 inch wide parallel to the leading edge and spaced approximately one-thousandth of an inch apart for a width of 0.025 inch. Figure 2 shows the general appearance and spacing. The various locations of the roughened areas are shown in the figures where the results are plotted. Three positions of roughness were tested, the farthest position back from the leading edge being 0.0157c. For the leading-edge position the roughened area was not centered about the leading edge but extended along one surface beginning at the leading edge. The leading edge position of roughness was tested on a cambered airfoil of medium thickness.

Lap joints such as those found on the wings of some all-metal airplanes were simulated on two N.A.C.A. 0012 airfoils by equal spacing of seven lap joints. On one airfoil the vertical side of the joints faced downstream and on the other they faced upstream. Two heights for each direction of facing were tested. The spacing of the joints and sizes are shown in the figures where the results are plotted. The 0.0004c height of joint may be considered to represent a scale reproduction of joints that might be found on some metal-covered airplane wings. The 0.001c height probably represents an extreme not likely to be reached in practice.

A surface simulating the roughness found on some wing walkways was formed on one of the metal N.A.C.A. 0012 models. The rough surface was obtained by using No. 180 carborundum sprayed onto a coat of fresh varnish. No. 180 carborundum grains average about 0.005 inch maximum dimension. This degree of roughness was chosen as representing to scale the roughness found on the walkways of certain airplanes now in service. The entire upper surface was coated.

RESULTS AND DISCUSSION

The results are presented as section characteristics in Figures 3 to 10, inclusive, in which the lift coefficient C_L, profile-drag coefficient C_{D_0}, and moment coefficient $C_{m_{c/4}}$ are plotted against angle of attack for infinite aspect ratio, α_0. The profile-drag coefficient C_{D_0} is also plotted against lift coefficient C_L.

Effect of over-all roughness on section characteristics.- The results from tests of an airfoil with two different surface conditions are compared with the results of a test made on a highly polished surface in Figure 3. The rough-emery finish caused the largest adverse effect on the airfoil characteristics. The results presented in Figure 3 show that polishing only the leading edge of the airfoil and leaving the remainder of the surface rough restored the value of the maximum lift coefficient to almost the normal value for the highly polished surface, and reduced the value of the drag coefficient to only slightly more than that for the standard polished airfoil. The machine-cut surface showed surprisingly little adverse effect.

The characteristics of a highly polished wooden airfoil, together with those of the same airfoil with a surface upon which no particular effort has been made to obtain a smooth surface, are plotted in Figure 4 for comparison with the characteristics of a standard polished metal airfoil. The failure of the highly polished wooden airfoil to check the results of the polished metal airfoil may be partly due to the severe conditions to which the model is subjected during compression and decompression of the air in the variable-density tunnel. Furthermore, the varnished surface is not as hard as the surface of a metal airfoil and small dust particles in the air stream which have no effect on metal airfoils might be expected to cause some roughening of the surface of a varnished wooden airfoil.

Variation of position of roughness.- The effect of the position of roughness on the upper and lower surfaces is shown in Figures 5 and 6. The greatest adverse effect is caused by the location of the rough area at the leading edge. As the location of the roughness is moved away from the leading edge, the adverse effects become smaller. When the rough area is directly over the point about which the leading-edge radius is taken, 0.016c from the leading edge, the adverse effects have almost entirely disappeared. The greatest adverse effect of leading-edge roughness is on the value of $C_{L_{max}}$, although the profile drag is also increased at high angles of attack. There is little effect on the value of the profile-drag coefficient at the low angles of attack. Rough areas on the lower surface of the airfoil cause some reduction in the value of $C_{L_{max}}$ but not as much as the corresponding location on the upper surface.

Effect of roughness depth.- The effect of striated areas of two depths of irregularities was investigated, one in which the depth was approximately 0.0005 inch (0.0001c) and the other in which the depth was approximately 0.001 inch (0.0002c). No detrimental effects caused by the striated area of lesser depth were found. The results of this test are not included in the figures since they come within the experimental error of checking the results of tests on the standard polished N.A.C.A. 0012.

Effect of nose roughness on the cambered airfoil.- The effect of roughening the leading edge of the N.A.C.A. 4412 airfoil is shown in Figure 7. A decrease in the value of $C_{L_{max}}$ for the N.A.C.A. 4412 of approximately 6 per cent was measured as compared to a decrease of 14 per cent in the value of $C_{L_{max}}$ for the N.A.C.A. 0012, the same location and degree of roughness being used in both cases. No increase in the value of the profile-drag coefficient or moment coefficient was evident at angles of attack within the normal high-speed flight range.

Surfaces simulating lap joints.- The effect of surfaces simulating lap joints of different heights and direction of facing is shown in Figures 8 and 9. No marked effect on the value of $C_{L_{max}}$ or on the value of the moment coefficient is indicated. The value of the profile-drag coefficient C_{D_o} is increased slightly over the entire angular range for all forms of the joint. There is apparently little choice as to which way the edge of the joint faces with respect to the air stream for the size joint which is common practice on airplanes at present. The test results from the airfoil with the large-size joint (0.001c) indicate that joints facing against the air stream have a slightly higher drag.

Surface simulating a wing walkway.- The effect of a surface simulating the roughness found on a wing walkway is shown in Figure 10. There is a large adverse effect on $C_{L_{max}}$ and C_{D_o}; the application of the rough surface to the airfoil caused a decrease of approximately one-half of the value of $C_{L_{max}}$ and an increase in the value of C_{D_o} to twice the normal value for the section throughout the high-speed flight range. The average height of this rough surface was sufficient to cause an effective camber change. (See $C_{m_{c/4}}$ curve.)

The effect of scale on a rough surface.- Some available data showing the scale effect on the maximum lift coefficient of an R.A.F. 30, 6 by 36 inch airfoil, have been included (fig. 11) to show variation of the maximum lift coefficient with a change in the value of the Reynolds Number. These data were obtained in the open-throat variable-density tunnel as described in reference 3. Several degrees of surface roughness were tested, ranging from a No. 180 carborundum-coated surface to a smoothly polished surface. Only the results of the extreme surface conditions are shown in the figure. As can be seen from Figure 11, the value of the maximum lift coefficient is little affected by the change in dynamic scale for the airfoil having the rough carborundum-coated surface as compared to the large favorable change for the same airfoil with a polished surface. The airfoil showed approximately the same lift characteristics at the lowest value of the Reynolds Number for all surfaces, but the difference between the characteristics of the airfoil with the rough surface and the airfoil with the smooth surface increased as the value of the Reynolds Number was increased. These results substantiate the previously held opinion that low-scale tests do not predict the seriousness of surface roughness on airfoil characteristics.

Surface-roughness effects on airfoil tests in general.- The results of the present investigation indicate that the aerodynamic characteristics of an airfoil may vary through a wide range depending upon the surface condition. This variation may be as much as that resulting from scale effect or that resulting from tests on an entirely different airfoil section. The importance of surface effect should be recognized in making comparative airfoil tests in wind tunnels and also when correlating test data from various wind tunnels, particularly at large values of the Reynolds Number. Airfoil surfaces must be aerodynamically smooth in order to eliminate the surface-roughness variable, an aerodynamically smooth surface being one whose excrescences and undulations are small and of such a nature that they do not affect to any measurable extent the flow characteristics over the surface. (Reference 4.) The present investigation indicates that for the model airfoils used in the variable-density tunnel an airfoil which has the nose well polished and which has an even and fair surface with few scratches, none of which are over 0.0001c in depth, is for all practical purposes aerodynamically smooth.

Practical considerations of surface roughness.- The present tests indicate that smoothness of the leading edge of the wing is important. Modern methods of finishing airplane wings, particularly those covered with fabric or plywood, make it possible to produce a smooth surface in most cases. The practice of extending a rough wing walkway forward to the leading edge of the wing is one common example in which a smooth leading edge is not obtained. Estimating the magnitude of the adverse effect of a rough walkway on the performance of an airplane is difficult on account of the proximity of the fuselage. The present investigation indicates, however, that a rough walkway carried to the leading edge of the wing may have a considerable adverse effect on the performance of a high-speed airplane.

The use on all-metal airplanes of a surface with lap joints similar to that tested in the present investigation is common. Consider as an example a commercial airplane having a wing area of 300 square feet and lap joints on the surface producing 0.0004c steps of the type investigated. With a top speed of 200 miles per hour, the additional drag due to the lap joints would amount to approximately 12 pounds and would consume 6.5 hp. Although this is a small part of the total horsepower, it is worth considering to the extent of fairing the edge of the plates by rounding the corners to a form similar to the fairing used in the protuberance tests as described in reference 5.

CONCLUSIONS

The present investigation, although of limited scope, admits of the following generalizations:

1. Tests on airfoils at high values of the Reynolds Number indicate that serious adverse effects on the aerodynamic characteristics are caused by surface roughnesses so small that they may ordinarily be overlooked.

2. The air flow over the leading edge of an airfoil is sensitive to both the location and size of irregularities within this region. Irregularities and scratches 0.0002c in depth and not more than 0.016c distant from the leading edge were found to be sufficient to cause measurable adverse effects.

3. Lap joints of the size commonly found in practice on all-metal covered wings have a measurable although small adverse effect on the airfoil characteristics within the normal flight range.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 15, 1933.

REFERENCES

1. Warner, Edward P.: Airplane Design, Chapter IX, pages 154-156, 1927.

2. Jacobs, Eastman N., and Abbott, Ira H.: The N.A.C.A. Variable-Density Wind Tunnel. T.R. No. 416, N.A.C.A., 1932.

3. Jacobs, Eastman N.: The Aerodynamic Characteristics of Eight Very Thick Airfoils from Tests in the Variable-Density Wind Tunnel. T.R. No. 391, N.A.C.A., 1931.

4. Fage, A., and Warsap, J. H.: The Effects of Turbulence and Surface Roughness on the Drag of a Circular Cylinder. R. & M. No. 1283, British A.R.C., 1929.

5. Jacobs, Eastman N.: Airfoil Section Characteristics as Affected by Protuberances. T.R. No. 446, N.A.C.A., 1932.

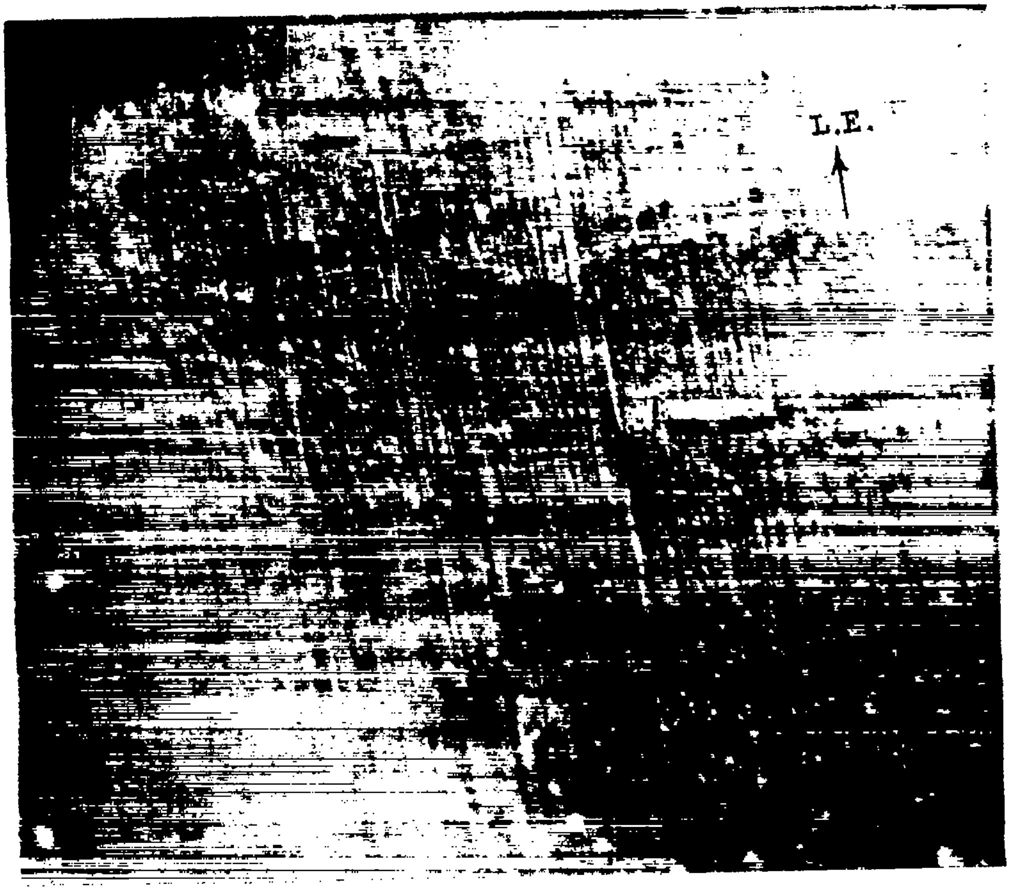

Figure 1.-Photomicrograph (×15) of the surface of the N.A.C.A.0012 airfoil as left by cutting tool of airfoil generating machine.

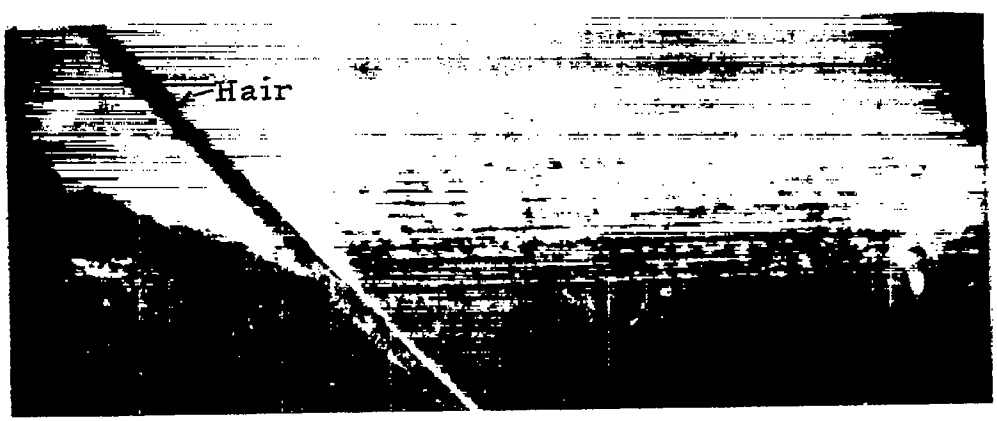

Figure 2.-Photomicrograph (×30) of rough area on N.A.C.A.0012 airfoil with human hair for comparison.

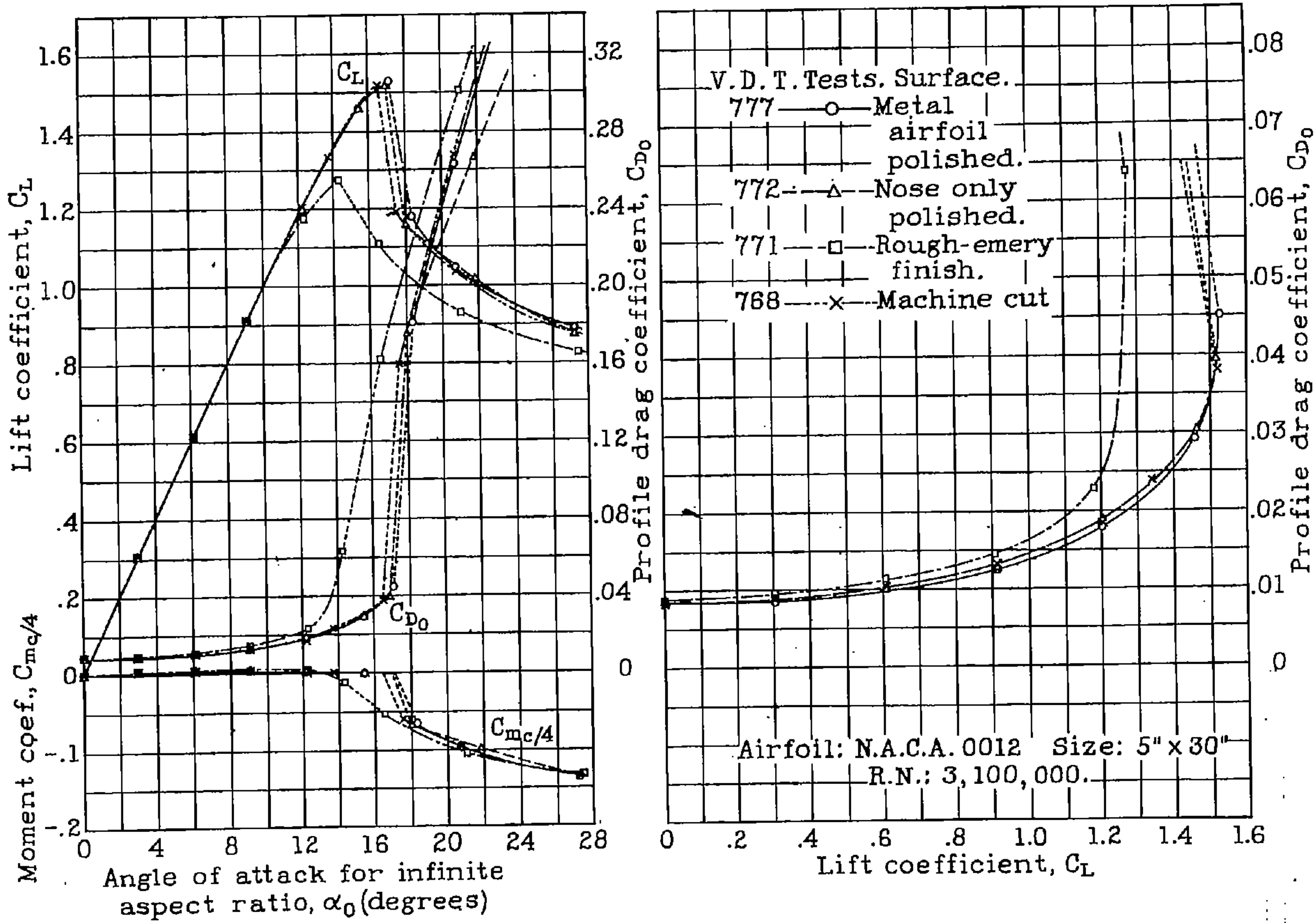

Figure 3.- Section characteristics as affected by various surface conditions.

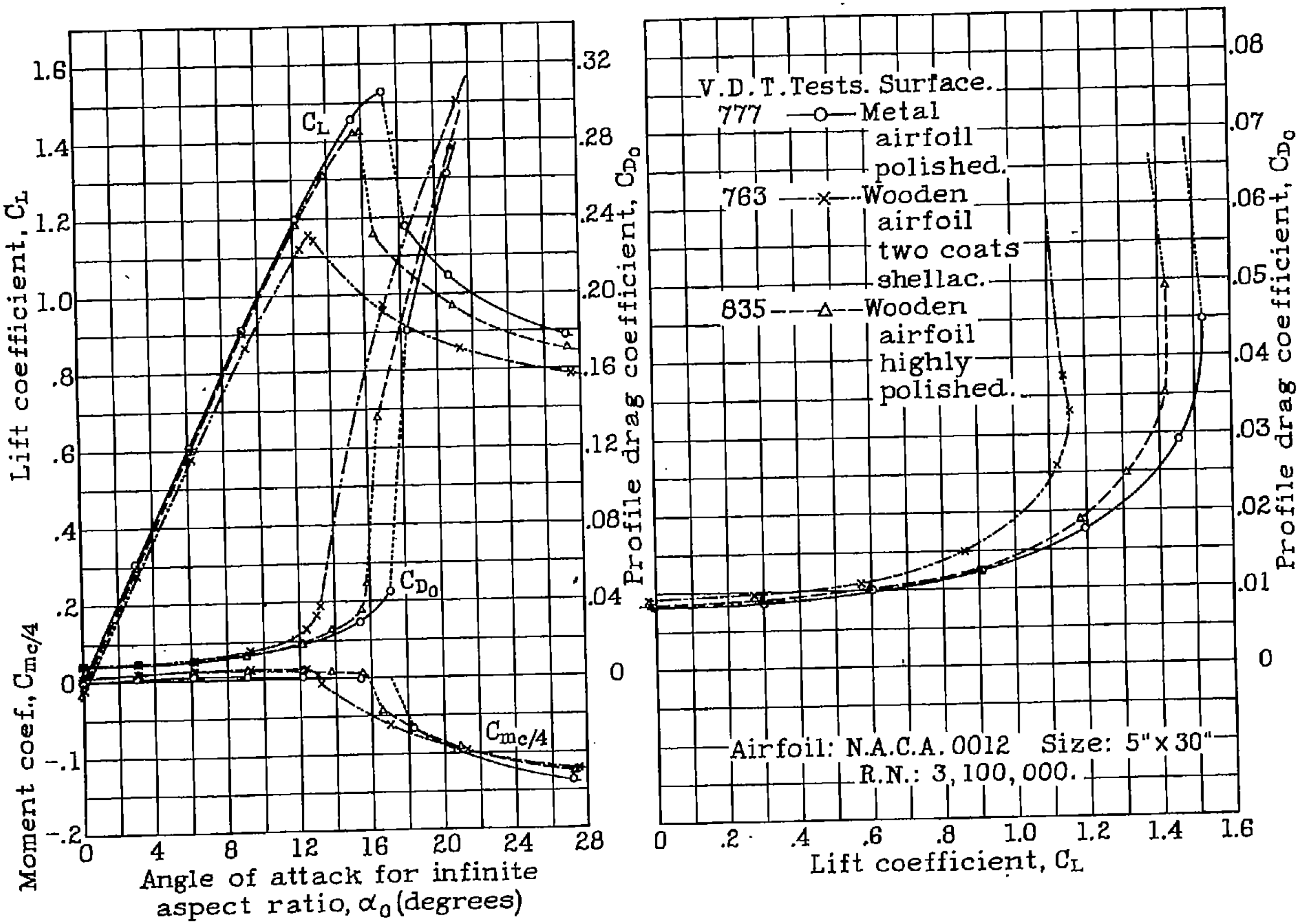

Figure 4.- Section characteristics of wooden airfoil with two surface conditions compared with those of the polished metal airfoil.

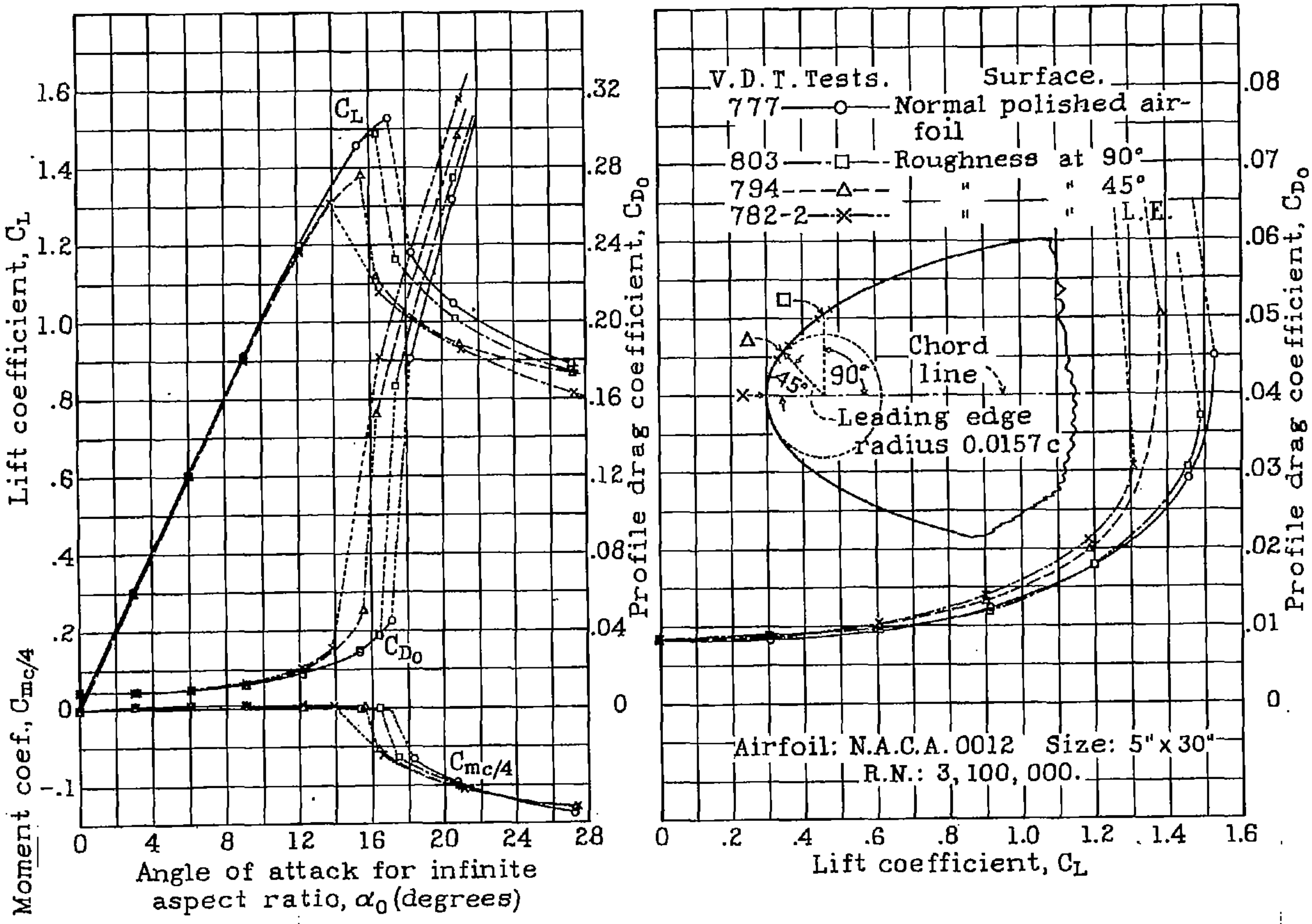

Figure 5.- Section characteristics as affected by location of surface roughness on upper surface near leading edge.

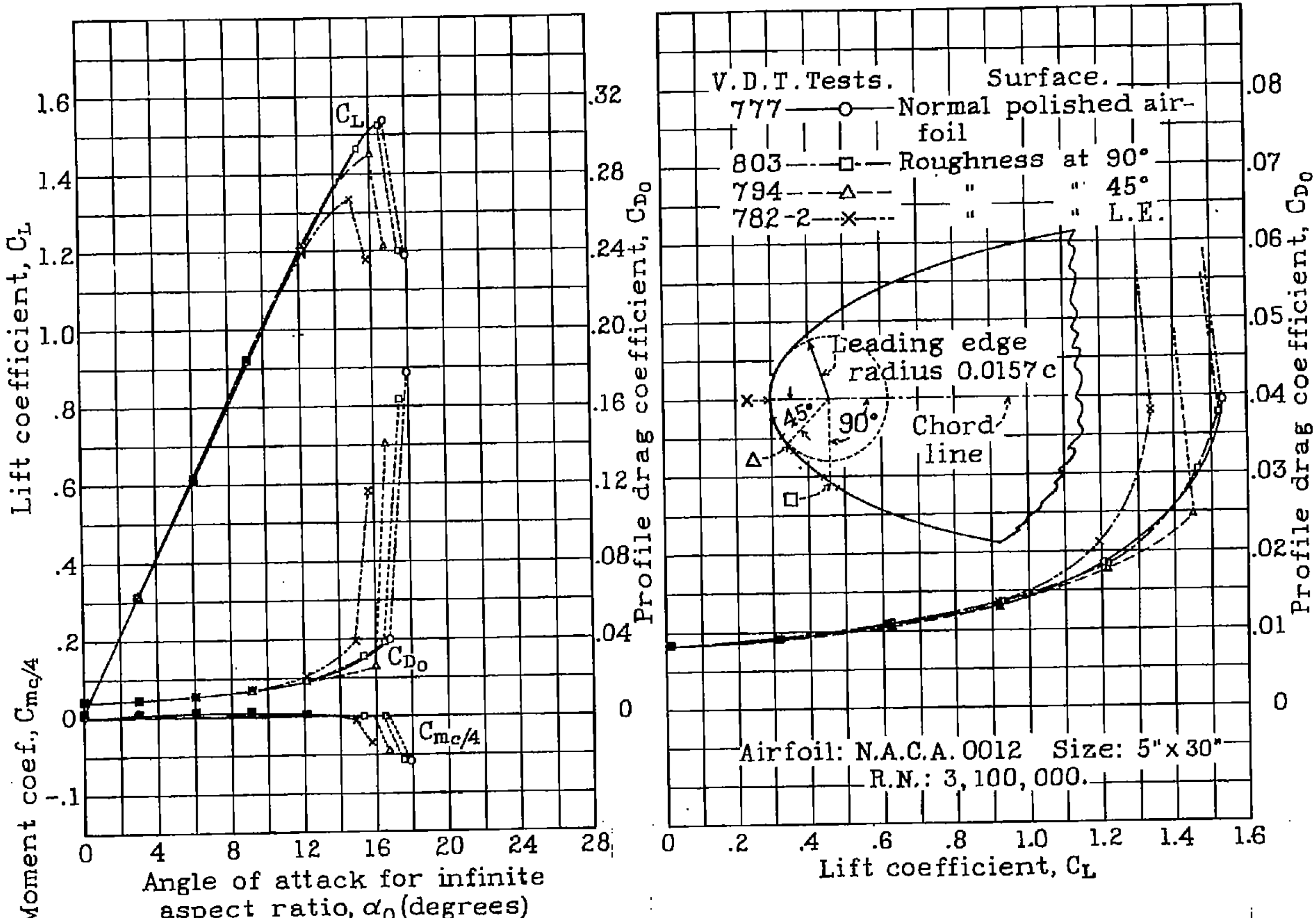

Figure 6.- Section characteristics as affected by location of surface roughness on lower surface near leading edge.

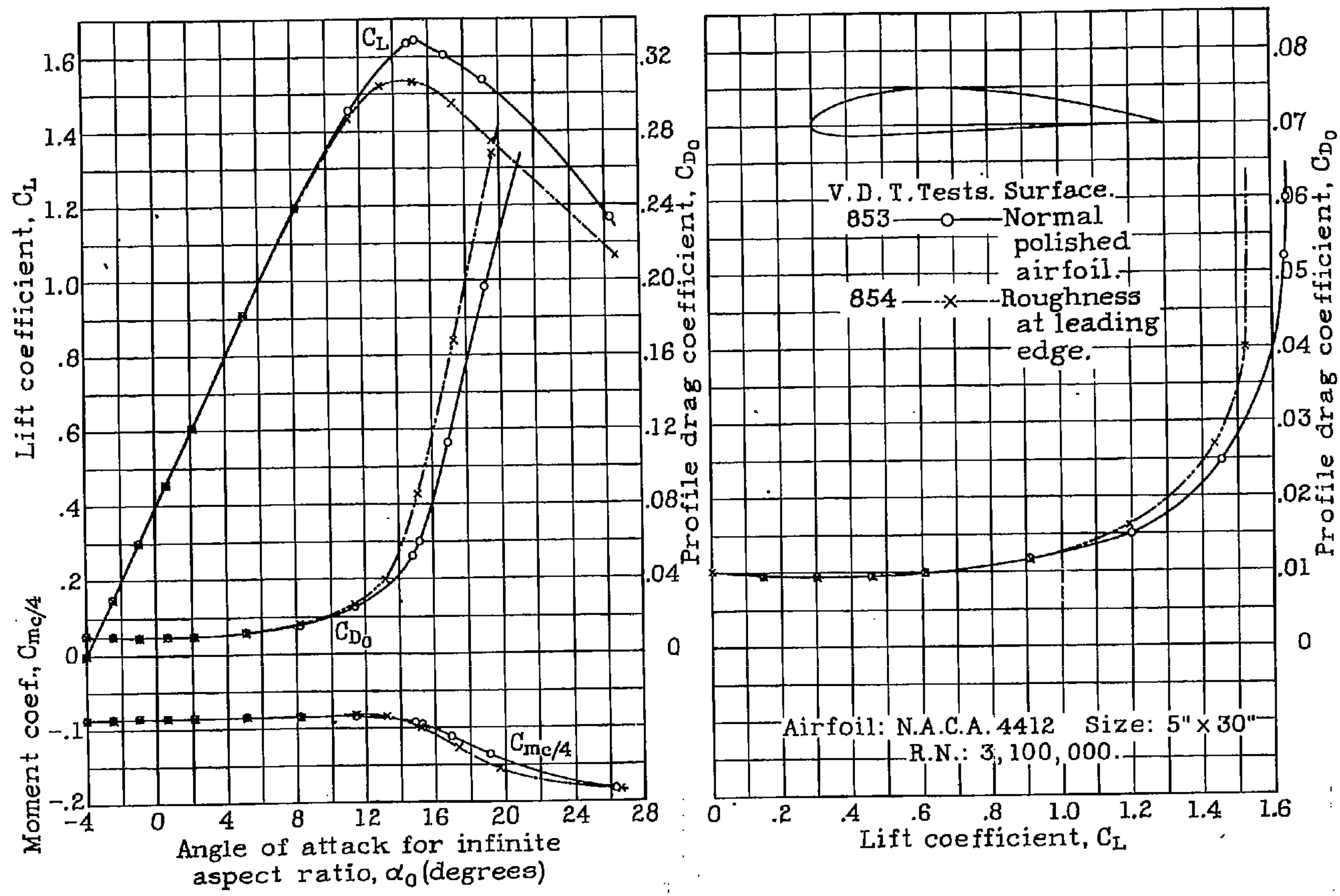

Figure 7.- Section characteristics as affected by roughness at leading edge.

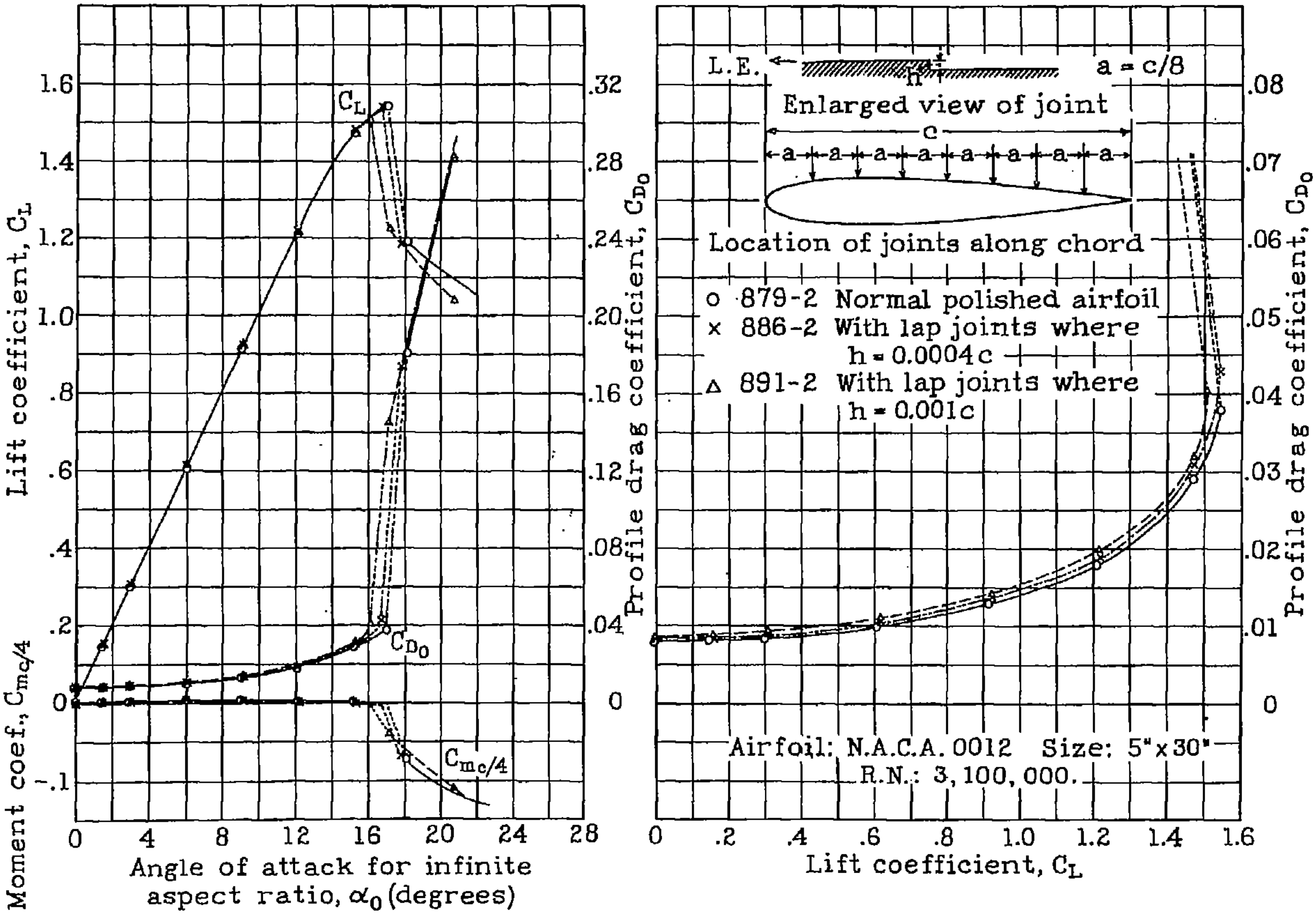

Figure 8.- Section characteristics as affected by surface simulating lap joints facing the trailing edge.

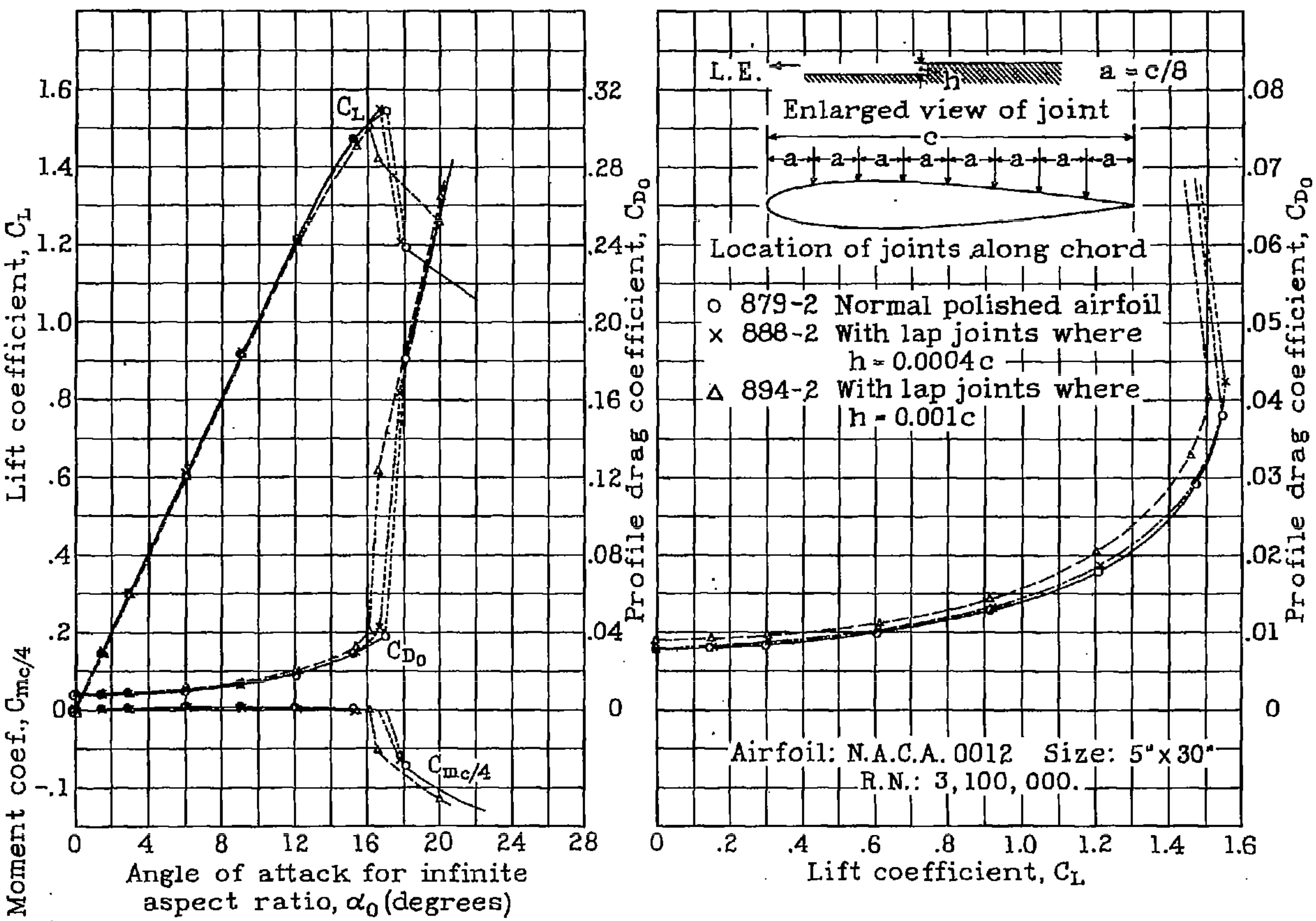

Figure 9.- Section characteristics as affected by surface simulating lap joints facing the leading edge.

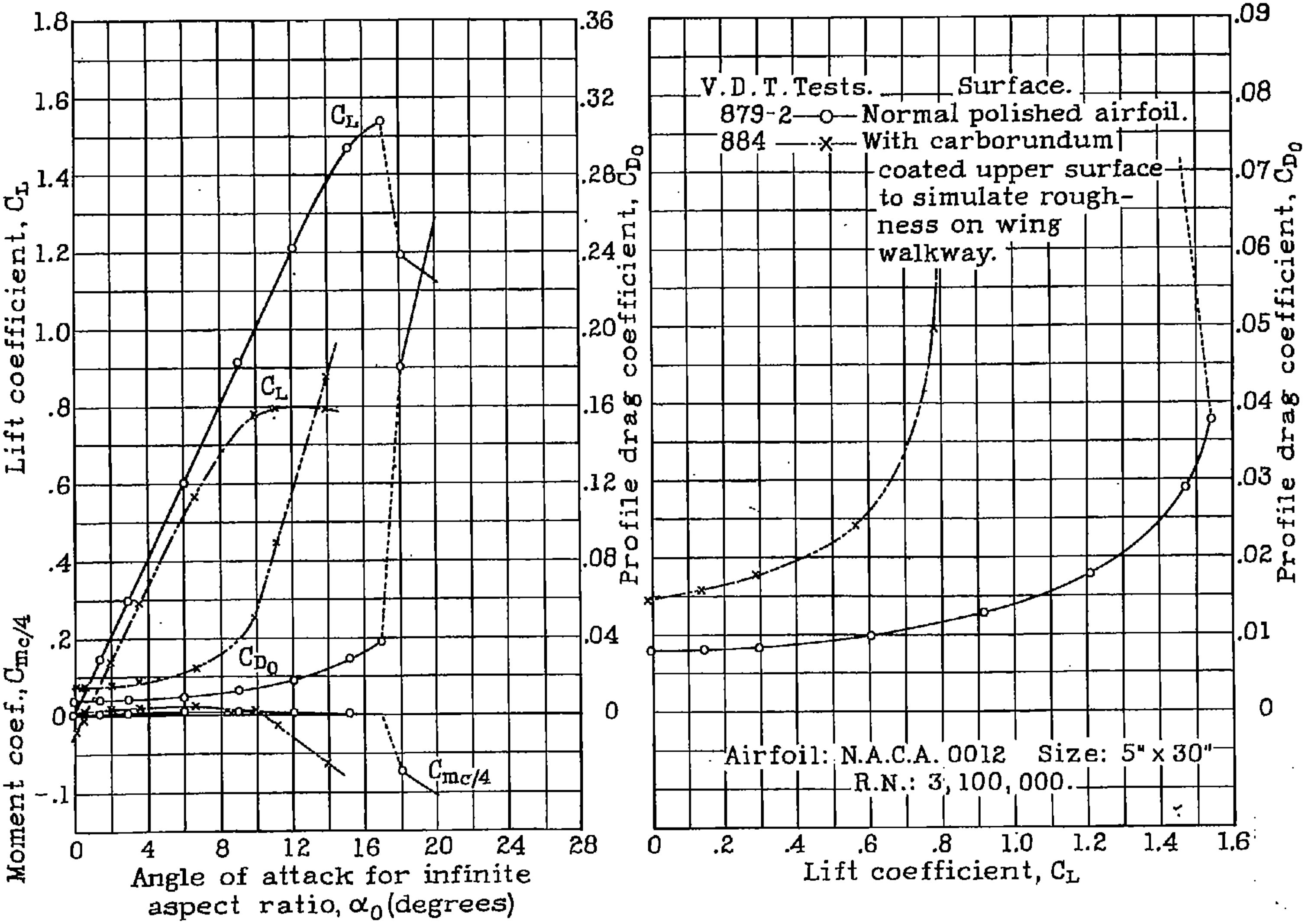

Figure 10.- Section characteristics as affected by very rough surface, (180 carborundum)

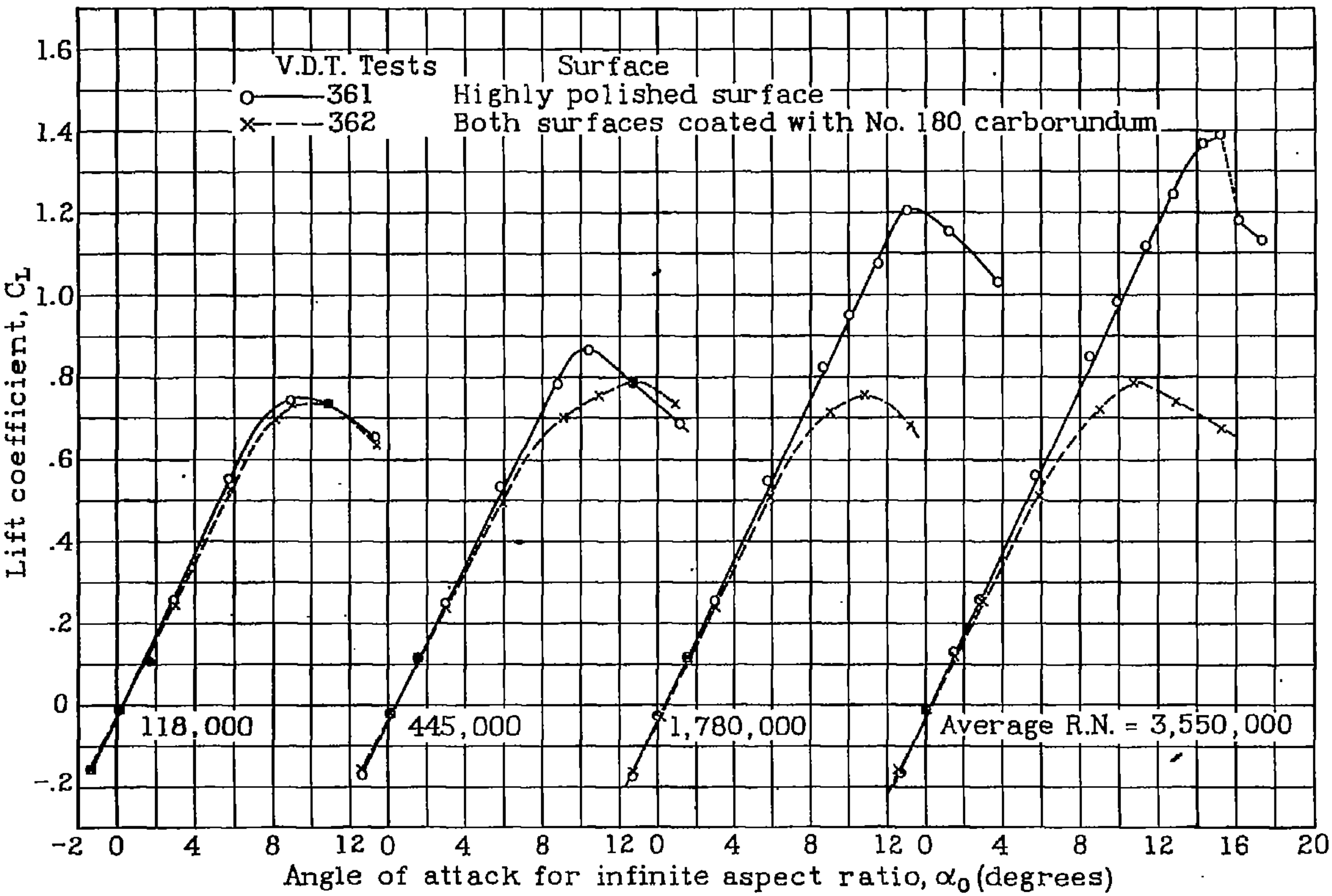

Figure 11.- Airfoil: R.A.F. 30 Size: 6" x 36"
Scale effect on the lift coefficient as affected by smooth and rough surfaces (open-throat tunnel tests).